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Steve Goodhew
Sustainable Technologies Group, Nottingham Trent University, UK


Jim Carfrae
Environmental Building Group, University of Plymouth, UK


Pieter De Wilde
Environmental Building Group, University of Plymouth, UK

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Institution of Civil Engineers

Briefing: Challenges related to straw bale construction

S. Goodhew MSc PhD, J. Carfrae BA and P. De Wilde MSc PhD

This briefing discusses the current challenges to the deployment of straw bale walling systems in the UK. A short historical context is described and the major areas of scientific interest are discussed. These areas include the environmental, thermal, acoustic, structural and durability performance of straw bale walling systems in relation to their properties. Current values and measurements of these properties are discussed along with a short introduction to the major researchers and institutions researching the design and attributes of straw bale walls. The briefing concludes that the evolution of straw bale walling systems is rapidly developing and can, when appropriate solutions to potential risk issues are used, provide the basis for comfortable and sustainable buildings.

1. INTRODUCTION

Straw bale buildings are still a relatively unfamiliar occurrence within the UK's building stock. However, the drivers for sustainable construction combined with a rising profile as a construction technique have increased the general awareness of this form of construction. This has led to an increasing number of buildings of this type being planned and constructed in the UK. The following sections of this briefing aim to outline the current position on this technology/material and to discuss the challenges associated with the structural and environmental issues connected with the use of straw bales as a construction technique.

1.1. History

The first 'true' straw bale-based walling systems originated in the sand hills of Nebraska at the turn of the 19th century, not long after the use of the first baling machines (King, 2006). Historical patents for bale walls date back to the 1880s in the US state of Indiana (Steen *et al*., 1994). A further series of older straw bale buildings include a two-storey ranch near Hyannis, Nebraska (SBAN, 2010) which was built between the turn of the last century and 1914, probably the oldest bale building still in use today.

The construction of straw bale buildings in the UK is relatively new. The first known building used for habitation (either domestic or commercial) was a small dwelling built in 1995 by Bob Matthews of the Institute for Social Inventions (Sustainable Build, 2000) which is still occupied. After a slow start the number of buildings has been rising more rapidly, with a marked increase in the past 5 years. The main interest in the technique thus far is from the self-build sector, and straw bale buildings are often domestic, both in use and scale. As a new technology, and sometimes held to being an esoteric form of construction, the use of straw bales is perhaps hampered by being seen to be the preserve of the eccentric individual. The first buildings in the UK were therefore mainly simple single-storey load-bearing structures, often built by community groups or volunteers attending straw bale 'raising days'. The use of straw bales as infill in a framed structure, and more recently, the development of straw bales in structural insulated panels, is presently encouraging a wider variety of building types. This has allowed some larger non-domestic buildings to be built, including for instance the Eco Depot (ModCell, 2010) in York (Institution of Civil Engineers (Yorkshire and Humberside) 'highly commended award'), offices and auction premises for Sworders Ltd (the largest straw bale building yet built in the UK) at Stansted, Essex, and a large sawmill for Greyfield Timber in Dartington, Devon (Landscope, 2010).

1.2. Categorisation of building forms

Straw bale buildings are often as diverse in form as the many owners, designers and constructors who build them. However, it is possible to categorise their structural form into two main types. Load-bearing and non-load-bearing designs refer to whether the straw within the walls directly supports the roof and any intermediate floors or whether another supporting framework is used, with the straw filling in between the structural elements. Hybrid technologies such as straw combined with a variety of other materials such as earth and lime can further extend the spectrum of categories. The original tradition of building with straw bales is load bearing and this is commonly seen to be the purest form of the use of straw bale walling, as this harks back to the first recorded buildings of this type in Nebraska, USA. Some of the major UK advocates of load-bearing straw bale walls are Barbara Jones and Bee Rowan of Amazon Nails, who have published much practical information concerning this form of straw bale building.

Non-load-bearing designs rely upon a load-bearing frame to take the weight of the roof and intermediate floors. This does introduce extra material into a building but provides the possibility of erecting a frame and roof, under which bales can

Figure 1. Structural timber framing with non-load-bearing straw bale walls sitting on cantilevered floor joists to provide a continuous insulating external envelope

be stored in dry conditions and other weather-dependent building operations can take place. Figures 1 and 2 show a timber-framed non-load-bearing straw bale building during construction. Note the timber upright members supporting the roof and the box-outs and inserted lintels to cater for the structural issues around doors and windows, and the insertion of straw bales between the horizontal timbers.

Valuable work in promoting and researching more sophisticated construction techniques for straw bales has been undertaken by Tom Woolley, as Professor of Architecture at Queen's University Belfast, contributing to the architectural and technical design of straw bale buildings. Professor Peter Walker, Director of the Building Research Establishment Centre for Innovative Construction Materials, University of Bath, has been responsible for recent research into many aspects of the use of straw bales, particularly in conjunction with Modcell structural insulated panels. Other innovators in the UK include Rob Buckley of Dorset Centre for Rural Skills, who built the straw bale pavilion at the groundbreaking Genesis Project in Somerset, and the architects at ARCO 2, who have used straw bales in many new school buildings, and have recently set up a company called 'Ecofab', promoting a prefabricated modular straw bale building solution that enabled the Bosvigo School, Truro, to be erected and weather tight in just 4 days (ecofab, 2010).

Figure 2. Straw bale infill between roof timbers provides thermal and sound insulation for a sawmill in south Devon

In the USA, Bruce King has edited the current standard work *Design of Straw Bale Buildings* (King, 2006), a seminal work particularly for its contribution to the structural aspects of straw bale walling design. In Europe the leading publication on the subject is *Building With Straw* by Gernot Minke and Friedeman Mahlke (Minke and Mahlke, 2005).

2. ENVIRONMENTAL CREDENTIALS

Straw, in the form of straw bales, is an agricultural by-product and because of the limited uses found for the 12 million tonnes produced annually in the UK, it can be viewed as a waste material. However, Strammit board, a rigid boarding material manufactured from compressed straw and adhesive used in the construction of internal partitions and ceilings, was in production in the UK until the late 1990s. Therefore, straw could be viewed as a mainstream material until that point.

A positive characteristic often attributed to the use of straw in buildings is that it contains little embodied energy. This description is a logical one but is sometimes difficult to substantiate. The Bath University *Inventory of Carbon and Energy* (Hammond and Jones, 2008) states that straw has an embodied energy quotient (cradle to gate) of 0·24 MJ/kg. This can be compared with existing construction materials in two ways. If we look at straw simply in its role as a non-load-bearing component then its primary job is to provide insulation, and that can be compared with an embodied energy quotient for thermal insulation of 35 MJ/kg. If, however, we consider straw used as a structural load-bearing wall element, we can compare it with different traditional walling materials as shown in Table 1.

Taking these figures in isolation could be misleading, as the figures for the conventional materials in Table 1 do not include the insulation that would have to be added to a domestic wall detail, which would significantly increase the embodied energy. The accuracy of the values can be debated, as a result of different assumptions regarding the densities of the materials, the quantity used in a wall and further details of the construction, but in general it appears safe to claim that the embodied energy values of traditional walling materials or general insulation are considerably higher than those of straw bales.

2.1. Thermal aspects

The thermal properties of straw bales depend upon the density of the bales. Load-bearing straw bale walls will require the bales to have a higher density, typically more than 110 kg/m^3. Non-load-bearing straw bales used for infill can tolerate lower densities, often in the range 80–100 kg/m^3. Different authors (Goodhew and Griffiths, 2005; Szokolay, 2004) quote thermal conductivities (λ) for straw bales that vary from 0·060 to 0·038 W/mK. A sensible mean can be taken from the results of a measurement to DIN 52612 (DIN, 1979) for a bale density of 90 kg/m^3 giving a thermal conductivity of 0·045 W/mK, as described by the German national organisation of straw bale building, FASBA (FASBA, 2010). It has also been noted that the conductivity for a bale placed on edge with the straws running perpendicular to heat flow is better than that of a bale placed on its flat side with the straws running parallel to heat flow. This allows for the construction of a wall of reduced width while still retaining the same overall U value, which is typically 0·165 W/m^2K (Munch-Andersen and Andersen, 2004).

Walling material	Embodied energy quotient (cradle to gate): MJ/kg
Facing bricks	8·20
Concrete block 10 MPa	0·67
Concrete block 13 MPa	0·81
Autoclaved aerated blocks	3·50

Table 1. Embodied energy quotient of traditional walling materials

2.2. Acoustics

Several anthologies of work devoted to the design and technical aspects of straw bale building quote relevant acoustic data. *Building With Straw* (Minke and Mahlke, 2005) refers to John Glassford at GrAT as stating that depending upon the frequency, a 45 cm thick straw wall, treated with appropriate render on both sides, gives a 'noise level difference of 43–55 dB'. The exact conditions under which the measurements were taken are not comprehensively stated, but these figures do offer a general guide. *Design of Straw Bale Buildings* (King, 2006) also quotes Glassford's work but also eludes to Mas and Everbach (1995) who measured the sound transmission of a '20 inch thick stuccoed wall of wheat and rye grass bales' with a resulting reduction of 59·8 dB. Danish Electronic, Light and Acoustics (DELTA, 2001) undertook in situ measurements to ISO standards from an internal straw bale partition dividing two rooms, reporting a value of 46 (−2) dB R′w (+ Ctr). However, the researchers felt that the figure would have been closer to 53–54 dB R′w if certain acoustic weaknesses, such as internal voids and discontinuities, had not existed. This conjecture is partly supported by a laboratory test published in *The Last Straw*, which provided a result of 53 dB R (R = laboratory testing value) (Dalmeijer, 2006).

In the UK, sound insulation measurements have been undertaken upon a series of load-bearing straw bale seminar rooms in the Genesis Centre at Somerset College of Arts and Technology, Taunton. These were undertaken according to ISO 140: 4–1998 (ISO, 1998) and the UK's Approved Document E procedure. With due regard for the limitations that an in situ measurement case study provides, the acoustic data collected from these tests suggest that it is possible for straw bale walls to achieve the minimum requirements of Part E with a range of values of 48–50 dB DnT,w + Ctr (Deverell *et al.*, 2009). Although inconclusive, the sound measurements undertaken upon various straw bale buildings suggest that for a relatively lightweight walling system, good sound insulation is not just a theoretical possibility but is achievable in situ.

3. STRUCTURAL PROPERTIES

The prime structural requirement for straw bale walling systems (and in the case of non-load-bearing systems, the combination of the straw and framing materials) is to withstand the live, dead and imposed loads inflicted by the general use of such a building. In the context of the structural role of straw bales, it is useful to consider the plastered straw bale wall as a composite material. Rigid materials used as renders, especially when allowed effectively to bond to straw bales, allow the render–bale system to act as one structural system, in which a transfer of load can take place between the outer render and the inner straw bale core. From an engineering point of view render–bale systems could be considered a form of stressed-skin panel, with the insulating core of straw positioning the outer layers of render in the same plane. The main forces that any straw bale walling needs to resist are compressive. The ability of any straw bale wall to withstand a compressive force relies not only on the density of each bale and the packing of the bales within a wall but also on the thickness and quality of the render and its boundary connections to the straw. Within non-load-bearing systems the downward forces from the upper floor and/or roof are transmitted through vertical, often lightweight, structural members either hidden within the wall or placed to the outside or the inside face of the wall. These vertical structural members are often located at the edges of openings, such as doors, windows or other discontinuities in the building façade. In some systems, the bales can be placed upon a platform that is cantilevered out from the floor, forming an extra insulating layer around the structure and living space. This cantilever can impose some different forces upon the other structural components that make up the other parts of the building. Structurally, methods exist that mix load-bearing with non-load-bearing technologies to allow the designer and/or builder to obtain the performance that they require.

Many studies have been undertaken to examine the effects of different loads on both rendered and unrendered straw bale walls. In the UK, work coordinated by Professor Peter Walker at the University of Bath investigated the compression load characteristics of five walls of different structural properties in laboratory conditions. The results varied from an ultimate load of 19·2 kN/m with 170 mm vertical deflection on an unrendered wall, compared with a the lime-rendered wall that withstood a maximum load of 66 kN/m with 55 mm of deflection (Walker, 2004).

The structural properties of bales made from different plants can, much as the thermal properties, vary according to the density of the bale. Rice straw used on the west coast of the USA is more resistant to compression than the wheat straw commonly used in the UK. A 2·4 m high stack of ordinary wheat straw will settle 50–75 mm under compression, whereas the rice straw wall will only give 10–20 mm (King, 2006).

It is usual in the context of a load-bearing straw bale wall to pre-compress the bales in order to reduce any initial settlement due to creep in the wall before rendering. There is some debate among practitioners as to how much compression to use and when. The traditional approach is to apply as much compression as the wall could take before visibly deforming, then construct the roof and finally apply the render. This method is increasingly being replaced with a hybrid approach in which a temporary lightweight frame able to support the loads of the roof structure during the construction phase is built first. The straw bale elements are added, and after rendering, it is the combined strengths of the straw and render composite with the framing that will take all the loads imposed upon the building.

As a result of the limited compressive strength of rendered straw bale wall structures, the generally accepted height limit using unframed, fully load-bearing straw bale construction is two storeys, and even this is difficult to achieve considering the structural limitations of load-bearing straw bale walls. However, the development of different framing techniques alongside the use of structural insulated straw bale panels is starting to expand the structural possibilities, allowing the appropriate use of straw bale construction for larger, and taller, buildings.

4. DURABILITY

Straw bale walls require a render or coating that will protect the straw from the weather while allowing any trapped moisture to escape. Traditional lime renders offer one solution and have protected many historic walls. In many instances lime is recommended as the main constituent of renders by organisations such as the UK's National Trust and the Society for the Protection of Ancient Buildings. However, for load-bearing straw bale walls, render or external plaster will resist some vertical and lateral loads. All corners around openings through a lime render need reinforcement, to reduce the incidence of cracking. Earth renders are becoming more popular but potentially need more maintenance than lime materials, and cannot as yet be recommended as an external finish on exposed façades. Both lime and earth renders require a lime or lime–earth wash final coating. A number of modern straw bale building walls have been protected using rain screens, some using natural materials such as timber and others using impervious modern materials such as profiled plastic and metal sheets.

Recent research at the University of Plymouth has been investigating the moisture performance of straw in construction, and the findings have demonstrated that the material could be more robust than previously thought. The normally agreed sensible limit to moisture content in most organic materials is 25% water content on a dry basis (percentage of water over dry weight of material), but laboratory tests, combined with investigation into a range of straw bale buildings, have shown that if the straw does not exceed the capillary saturation point (approximately 37%) for long periods of time, over several months it will dry out with no apparent damage. Buildings' walls have been measured in situ with moisture levels that have been above 25% for months without long-term damage beyond a little discoloration. The use of vapour-permeable finishes is essential here, as they will allow the straw to dry out over time. These high levels of moisture are unusual, however, and in a properly constructed straw bale wall exposed to the temperate maritime climate typical of the UK, the moisture levels will be approximately 15%, with a clear gradient from 10% in the heated side of a domestic wall to 17% on the outside. The use of a rain screen will typically lower the moisture content of the straw on the outside face of the wall by approximately 3·5% and is therefore a clear recommendation for exposed situations (Carfrae *et al*., 2009).

As with all organic materials used in construction, the use of appropriate detailing is essential, because whereas non-organic materials can experience leaks and dry out, organic materials are not so forgiving. This is becoming an area of increasing importance in modern buildings as a result of the need for good airtightness specified in current and future codes, so to a certain extent the detailing of a building to prevent moisture penetration can be combined with the concerns of air infiltration.

5. REGULATION AND THE FUTURE

As the number of straw bale buildings being built grows, the need for codes of practice also increases. The first known international building permit for a straw bale building was awarded in 1989 in New York State (Hainer, 2007). At present there are no specific requirements/instructions for straw bale construction in the UK Building Regulations, but straw bale walls can comfortably conform to the generic criteria concerning health and safety, fire resistance and energy efficiency. As far as is known, no straw bale building in the UK that has been granted planning permission has yet failed to receive a building control certificate.

Fire safety is the area that many, including lenders and insurers, question with regard to the use of straw in buildings, but straw bales are remarkably resistant to the spread of fire for two main reasons. First, a bale of straw is too dense to burn properly unless the strings that hold it together come apart. Second, the almost universal use of render as a finish on both sides of the wall dramatically increases resistance to the transmission of both flame and heat. Testing has been carried out in Europe, Australia and America and in each case the required standard was met. In 2006 two walls passed the ASTM E119 (ASTM, 2008) standard, with a load-bearing earth-rendered wall passing the 1 h test, and a lime-rendered wall passing the 2 h test.

There is no direct reference to straw bales in the new UK planning policy statements, but with increasing concern for not just reducing the long-term energy demands of buildings but also the embodied energy used in their construction, it is clear that the use of straw bales can meet many of the increasingly stringent building requirements.

Straw bales are a co-product of the agricultural industry, and have absorbed carbon dioxide while growing as a crop. This, combined with the excellent thermal properties they exhibit, makes them an ideal choice for use in genuinely low-energy buildings. The Carfrae House in Totnes, Devon, won the Federation of Master Builders award for eco-house of the year in 2007, and has a primary energy use that conforms to the German PassivHaus standard (currently the most stringent in Europe).

6. CONCLUSION

The barriers to the effective use of straw and other non-food crop materials can be overcome by using simple and available technologies and practices. Protection from moisture ingress both from below using appropriate damp-proofing, from above using reliable roofing construction, and from driving rain through the use of good-quality lime renders, possibly in conjunction with rain screening, will greatly reduce the moisture-related degradation of any straw walls. Internal party wall partitions constructed from straw bales laid on their short sides, with due regard to gaps and completeness, can produce walls that will satisfy most regulations related to sound insulation. However, the excellent thermal aspects associated with straw walls can be compromised if openings or the structure of the building bridges the thermal path between the internal and external walls.

Constructing with straw has great potential where wall space is not at a premium. The physical attributes of the material can provide comfortable, appropriate buildings. As the number of buildings constructed with straw bales increases and volume production is contemplated, further issues including financial considerations, lack of appropriately skilled operatives and designers with experience, and limitations associated with material supplies may also become more important. However, if high-quality, integral straw bale units can be produced offsite, or individual bales are used in conjunction with exemplary detailing and construction, many issues concerning building with straw, both with site personnel (skills issues), designers, potential owners, lenders and insurers can be overcome.

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